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BIDIRECTIONAL CONTROL OF MYOELECTRIC PROSTHESES IN UPPER LIMB AMPUTEES: CURRENT RESULTS AND EXPECTATIONS

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DVOSMERNA KONTROLA MIOELEKTRIČNIH PROTEZA KOD PACIJENATA SA AMPUTACIJAMA GORNJIH EKSTREMITETA: SADAŠANJI REZULTATI I OČEKIVANJA

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ABSTRACT

The most common causes of upper-limb amputations include traumatic etiology and malignity, followed by peripheral vascular diseases. Prosthetic fitting along with conducting a rehabilitation program provide the greatest possible degree of independence to the upper-limb amputees in performing their daily tasks, occupational, recreational and work activities. Despite recent advance in strategies of design and control, the lack of sensory feedback is, according to patients, one of the most important characteristics lacked by commercial myoelectric prostheses. This reason has led to the need for the development of comprehensive prosthetic part which would provide intuitive control and realistic sensory feedback to the amputees enabling them thus to more easily accomplish the tasks which are essential for easier performance of activities of daily life. Electromyography, and recently, electroneurography signals have been used for the development of more efficacious upper-limb prosthetic control. Several recent studies have demonstrated the efficacy of homologous and somatotopic approach in upper-limb amputees, by applying implanted and surface electrodes. This work presents novel methods for effective bidirectional control of myoelectric prostheses in patients with upper-limb amputations using motor control and sensory feedback. The above-mentioned approaches are applicable and have good prospects in further clinical use. The intraneural, extraneural and surface approach can be more or less applicable depending on the etiology and the level of amputation. From a clinical point of view, various approaches should be combined for obtaining more efficient control of bidirectional prostheses and corresponding sensory feedback.

Keywords: *sepsis, Upper-limb amputations, sensory feedback, myoelectric prostheses*

SAŽETAK

Uzroci amputacije gornjih ekstremiteta su najčešće traumatske ili onkološke etiologije, praćene perifernim vaskularnim bolestima. Protetsko opremanje uz sprovođenje programa rehabilitacije pruža najveći mogući stepen nezavisnosti amputiranim gornjim ekstremiteta u funkcionisanju prilikom svakodnevnih profesionalnih, rekreativnih i radnih aktivnosti. Uprkos nedavnom napretku u strategijama projektovanja i kontrole, nedostatak senzorne povratne sprege je, prema oceni pacijenata, jedna od najvažnijih karakteristika koje nedostaju komercijalnim mioelektričnim protezama. Iz ovog razloga je došlo do potrebe za razvojem sveobuhvatnog protetskog dela koji bi ovim osobama pružio intuitivnu kontrolu i realističnu senzornu povratnu informaciju omogućavajući im da na taj način lakše izvršavaju zadatke koji su neophodni za obavljanje svakodnevnih aktivnosti. Elektromiografija, a odnedavno i elektroneurografski signali koriste se za razvoj efikasnije protetske kontrole gornjih ekstremiteta. Nekoliko novijih studija pokazalo je efikasnost homolognog i somatotopnog pristupa kod amputiranih gornjih ekstremiteta, primenom implantiranih i površinskih elektroda. U ovom radu su predstavljene nove metode efikasne dvosmerne kontrole mioelektričnih proteza kod pacijenata sa amputacijama gornjih ekstremiteta koristeći motornu kontrolu i senzorne povratne informacije. Gore navedeni pristupi su primenljivi i imaju dobre izglede u daljoj kliničkoj upotrebi. Intraneuralni, ekstraneuralni i površinski pristup mogu biti manje ili više primenljivi u zavisnosti od etiologije i nivoa amputacije. Sa kliničke tačke gledišta, trebalo bi kombinovati različite pristupe za dobijanje efikasnije kontrole dvosmernih proteza i odgovarajućih senzornih povratnih informacija.

Ključne reči: *Amputacije gornjih ekstremiteta, senzorna povratna informacija, mioelektrične proteze*

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INTRODUCTION

Acquired and congenital limb deficiencies occur in a significant number all over the world. Amputations are performed because of vital indications which require removal of limbs which are no longer functional, either because of the injury or disease. The most common causes of upper-limb amputations include traumatic etiology and malignity, followed by peripheral vascular diseases. Genetic variations and mutations are typical causes of congenital limb deficiencies. The upper-limb loss is more often caused by trauma in younger patients, while lower-limb amputations are more often present in elderly population, within which vascular etiology is predominant. At the beginning of 20th century, with growing industrialization, the number of workplace injuries increased, which is also accompanied by traumatic upper-limb amputations (1, 2).

The incidence of upper-limb amputations in the European countries is from 50 to 270 a year, with the total of 1900 amputations a year caused by traumatic etiology. It is estimated that the number of upper-limb amputees in the European Union amounts to 94000 (1). By 2050 it is projected that there will be up to 3.6 million people with limb loss living in the United States of America (2).

Excluding finger amputations, the most common upper-limb amputations occur at the transradial level, comprising thus 31% of all upper-limb amputations. Transhumeral amputation occurs in 28% of cases. The male population is more often affected by amputation, with 75.7%. Sixty percent of upper-limb amputees are between 21 and 64 years old, while there are 10% of amputees who are younger than 21 (3, 4).

Among all the physical factors which affect the treatment and functional potential of all amputees, the "amputation level" is most important. This "level" refers to a certain height of amputation which determines the effective length, power and mobility of the remaining part of the limb. The amount of physical functions which can be potentially retrieved primarily depends on the number of anatomic joints which have been lost and a patient's general condition, which is also associated with the age. The upper-limb amputation results in the loss of functionality, skillfulness, flexibility and sensory sensitivity (5, 6). Prosthetic fitting along with conducting a rehabilitation program contributes to reducing the above-mentioned losses and providing the greatest possible degree of independence to the upper-limb amputees in performing their daily tasks, occupational, recreational and work activities (5, 6).

Upper limb prostheses can be functional, cosmetic or special-purpose, while according to the control mechanism they use, they can be divided into body-powered, externally powered (myoelectric and electric) and the hybrid ones which represent the combination of the above-mentioned types (5, 6). The advantages of cosmetic prostheses include good appearance, light weight, low cost and easy usage, while their greatest shortcoming is the lack of functionality. Body-powered prostheses have an affordable price, good "feedback", they are easy to maintain, reliable and enduring, while their disadvantage is the necessity of suspension and body movements which are important for prosthesis control. The advantages of myoelectric prostheses include good control and appearance, without the expenditure of energy during use. Such prostheses do not require a suspension system or cables, and provide a good grip force. Their shortcomings include bigger cost, more costly maintenance, the use of battery for their operation and not being projected for hard physical work (7).

A common method of myoelectric prosthesis control includes electromyography (EMG) signals which are generated by muscle contractions, providing thus a greater number of available grip patterns with little additional complication for a patient. Another recent improvement of upper-limb prosthetics is the use of electroneurography (ENG) signals, which require direct bonding with the periphery nervous system (PNS) or central nervous system (CNS). Despite recent advance in strategies of design and control, the lack of sensory feedback is, according to patients, one of the most important characteristics lacked by commercial myoelectric prostheses. This reason has led to the need for the development of comprehensive prosthetic part which would provide intuitive control and realistic sensory feedback to the amputees enabling them thus to more easily accomplish the tasks which are essential for easier performance of activities of daily life (7, 8).

Sensory feedback strategies can commonly be classified along two dimensions. First, approaches can be categorized as either non-homologous, where feedback is provided via a different sensory modality (e.g., electrotactile or vibrotactile stimulation of the skin to convey pressure), or homologous, where the restored sensation matches the original sensation (e.g., invasive electrical stimulation of the sensory fibers innervating the hand) (8). Secondly, approaches can be categorized as either somatotopic, where the induced sensations are felt as originating from the correct region (e.g., sensation is felt on the phantom limb), or non-somatotopic, where the sensations are felt in an unrelated region (e.g., vibrotactile stimulation of the skin on the arm to convey touch events on the hand) (9).

Electromyography, and recently, electroneurography signals have been used for the development of more efficacious upper-limb prosthetic control. Several recent studies have demonstrated the efficacy of homologous and somatotopic approach in upper-limb amputees, by applying implanted and surface electrodes.

NEW METHODS WITH MOTOR CONTROL OF MYOELECTRIC PROSTHESES

Intramuscular control

For the first time, in 2014, Paul Pasquina et al. (10) demonstrated the method of complete implantation of myoelectric sensors, for control of enhanced electromechanic hand in patients with transradial amputation. The aim of their research was to enhance versatility and complexity of tasks the patient carries out while using a myoelectric prosthesis in activities of daily living, in comparison to the achievements with a previous myoelectric prosthesis. They noticed that available prosthetic devices, controlled by electrical potentials from residual muscles, which are recorded by surface electrodes on the skin, are often characterized as non-reliable. This leads to a high level of rejection and abandonment of upper-limb prosthetic devices (11). It is reported that surface electrodes have a limited function, due to poor contact with the skin, pistoning at the prosthetic liner-socket inteface, sweating of the stump and the ability to record signals only from surface muscles, which is not sufficient for achieving the desired function of the prosthesis. More sophisticated devices require stable and reliable interface between the user and a myoelectric hand to improve function of the upper limb prosthesis. We have used Implantable Myoelectric Sensors (IMES), which represent small electrodes placed into the forearm muscle, whose purpose is to detect and wirelessly convey a myoelectric signal to the prosthesis by means of electromagnetic coil built into the socket (12). The purpose of this system is to enable simultaneous reception of signal from the stump muscles, while enabling natural control of prosthesis with a higher level of freedom. Their first subject reported he was capable of performing more versatile and more complex tasks in everyday life in comparison to what he could do with his previous myoelectric prosthesis. Preliminary results of this study show the applicability of IMES technology for reliable detection and wireless transfer of myoelectric signal from the stump muscle for the purpose of achieving more intuitive control of the prosthesis.

Neural control

Silvestro Micera (13) et al. in 2011 worked on deciphering information from neural signals recorded by means of intraneural electrodes, with the aim to develop neuro-controlled arm prosthesis. The option of controlling more sophisticated arm prostheses by use of direct connection with the nervous system is especially interesting from the aspect of improving a patient's quality of life. The use of intrafascicular electrodes which are placed on peripheral nerves proved to be an excellent option because of its high selectivity and relatively low invasivity. Their use and the possibility of deciphering a variety of information from sensorial and motor channels were tested with the aim to develop an ultimate algorithm which would be used for the control of neuro-controlled arm prostheses. The results have shown that the combination of recordings from different locations and advanced technique of signal processing can be used for identification of sensor impulses and motor commands. This method has been subjected to pre-testing on patient volunteers and proved to be promising.

Paolo M. Rossini (14) et al. in 2010 used an implant with a double nerve intraneural interface for better control and use of below-elbow prosthesis with a higher degree of freedom. The main principle on which this project was based is the position that neurons and CNS partly carry on their function and can be used for control of a myoelectric prosthesis, despite neural remapping after the upper-limb amputation. The aim of this study is to evaluate new peripheral intraneural myoelectrodes for control of prosthetic arm movements and for sensory feedback, with assessment of cortical reorganization by following a restored data flow. Four intrafascicular longitudinal flexible multielectrodes (tF-LIFE4) were placed into the medial and ulnar nerves of an amputee while recording output signals for the duration of 4 weeks. Classifiers of artificial intelligence were used off-line for the analysis of LIFE signals recorded during three different hand movements under voluntary control. The results have indicated that real-time control of motor response was achieved in three weeks. Being used off-line, artificial intelligence reached >85% of correct trial classification in the real time. Besides, different types of electro-stimulation were used for achieving localized sensations on hands/fingers. Cortical organization was monitored by means of transcranial magnetic stimulation, simultaneously with partial withdrawal of symptoms caused by phantom limb syndrome (15). It was concluded that tF-LIFE4 electrodes were recording output signals transferred by nerves during 4 weeks, although the efficacy of sensory stimulation decreased after 10 days. Recording signals from numerous nerve fibers enabled correct classification of high percentage of different actions.

Francesco M. Petrini et al. (16) in 2019 conducted a six-month clinical study which included three patients with transradial amputation who had transversal intrafascicular multichannel electrodes (TIMEs) implanted into the medial and ulnar nerves (17). Electrical stimulation was performed by means of electrodes connected with artificial sensors in the prosthetic fingers for obtaining sensorial feedback that subjects could use while carrying out different grip tasks. All subjects, regardless of significant clinical differences among them, reported occurrence of sensations elicited by stimulation in the phantom hand throughout the entire duration of the trial. They also efficiently incorporated sensory feedback into their strategy of motor control while performing experimental tests simulating tasks from real life (with and without visual support). Finally, the subjects reported decrease of phantom pain and improvement of overall mood. Promising results which were achieved with all subjects confirm the possibility of the use of intraneural stimulation in clinical conditions.

NEW METHODS FOR CONTROL OF MYOELECTRIC PROSTHESES WITH RESTORATION OF SENSORY FEEDBACK

Non-invasive methods of sensory substitution

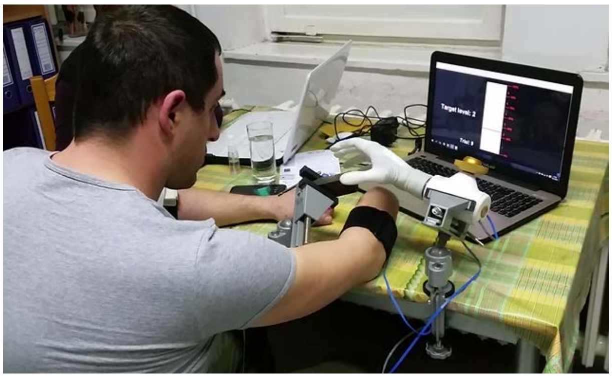
Popovic I. et al. in 2015. showed results of the use of sensory substitution by surface electrical stimulation which activated remaining sensory structures in below-elbow amputees (18). Apart from contributing to better functionality and greater degree of self-confidence of the users (19), availability of prosthetic feedback can also help decrease the phantom pain (20). When speaking about afferent electrostimulation, former studies have shown that healthy subjects can discern sensations which occur as a consequence of current impulse width modulation, frequency or site of electrostimulation applied on the forearm (21). The aim of this research was to investigate whether it is possible, despite changes in the physiology of sensory nerve fibers which arise as a consequence of amputation, to send feedback to the transradial amputees, by means of the system of coded messages which are transferred by surface electrostimulation of the residual stump. The planned study was prospective and it was conducted in the Specialized Hospital for Rehabilitation and Orthopedic Prosthetics in Belgrade, in business and technical cooperation with Tecnalia Serbia Ltd., Belgrade, Serbia. The study included three subjects with the transradial level of amputation, with a median age of 50± years. Trauma was the cause of amputation in all subjects, with the right hand being dominant before the amputation. The equipment for electrostimulation consisted of a stimulation electrode with multiple pads and an electrical stimulator IntFES v2 and a stimulation electrode with 16 pads placed circularly around the forearm (the amputation stump) of the users, so that the centre of the electrode was on the central volar part of the forearm.

Picture 1. System for electrotactile stimulation placed on the amputation stump

The amplitude for each pad on the electrode was adjusted in a way which enabled us to evoke the sensation which was clear and understandable and not the least unpleasant. The purpose of the conducted measurement was to investigate the understanding of various types of information which was coded by stimulus location and stimulation frequency. The subjects first went through a short training session where they got acquainted with eight different messages which corresponded to certain processes occurring on the prosthesis (hand opening/closing, pronation/supination, flexion/extension and decrease/increase of force). During a training session, subjects were supposed to recognize which type of the above-mentioned information was sent to them. The results of the study showed that patients with transradial amputation, after a short training session, were able to recognize the set of information transferred by surface electrical stimulation with high accuracy. The obtained results suggest that the used system and protocol can be applied in most persons with transradial amputation and that differences in sex, age, side and level of amputation, as well as the time since amputation should not have an important role.

Popovic I. et al. in 2016 continued investigation regarding sensory substitution by surface electrical stimulation (22). The investigation was performed because it was noticed that the main disadvantage of myoelectric prostheses was the absence of the feedback regarding proprioception and the applied grip force (23). The aim of the investigation was to examine whether a subject can control the applied force when using myoelectric prosthesis with the help of electrotactile stimulation. The grip force applied by a prosthetic hand is considered one of the most useful information that can be transferred to the user because it cannot be determined on the basis of visual inspection and it was most frequently used in the previous researches. The planned research was a prospective study and it was conducted in the Specialized Hospital for Rehabilitation and Orthopedic Prosthetics, Belgrade, in business and technical cooperation with Tecnalia Serbia Ltd., Belgrade, Serbia. The study included five subjects (4 males and 1 female; 3 right-sided and 2 left-sided transradial amputations), average age ±48, traumatic etiology, with the right hand as dominant before the amputation. The equipment that was used included "Michelangelo" prosthetic hand with an active electrode for recording muscle activity (Otto Bock Healthcare GmbH, Vienna, Austria), a multichannel system for surface electrical stimulation (MaxSens, Tecnalia, San Sebastian, Spain) and a laptop computer (24). The system for stimulation consisted of an electrical stimulator and an electrode with 16 pads which was placed circularly around a subject's forearm (the amputation stump, so that the center of the electrode was on the central volar part of the forearm. Myoelectric prosthesis and a system for stimulation through wireless connection communicate with a computer, which has a control loop implemented for closed-loop prosthesis control with electrotactile feedback. During evaluation of grip force control, subjects had to perform a contraction of adequate size so as to close the prosthesis and grasp an item applying the requested force. Among 6 levels of force which were coded by electrical stimulation, 4 medium levels were repeating themselves as tasks of an accidental choice. The experiment was divided into three sessions. The first and last session were without the feedback and consisted of 60 grips. In the second session (training), which involved 120 grips, the subjects used a closed-loop control method. Before the second session, subjects were trained to accurately interpret electrical stimulation and recognize the feedback. In the last session, the subjects managed to, after cancelling the feedback, maintain the same level of output as in the previous training session via a closed-loop system (22, 23).

Picture 2. Experimental setup



The subject is controlling a prosthetic arm by means of an electrode which is placed on the amputation stump and a stimulation electrode through which the feedback is transferred. The computer screen shows the requested level of force which has to be applied by the subject.

The results of the study show that the subjects' performance is better during control of prosthetic grip force when there is a feedback, i.e. when the subject receives coded information about the implemented force by means of surface electrical stimulation. It has been indicated that there was a short-term learning of control due to existing feedback.

The other group of researchers in 2017 investigated the possibility of using transcutaneous electrical nerve stimulation to elicit reflex sensation in upper-limb amputees, as well as their application during use of bidirectional prostheses (25). This work shows the method of noninvasive electrical stimulation of the medial and ulnar nerve, which preserved some of the advantages of the invasive approaches, such as a scheme of homologous provision of sensory feedback. With the aim to investigate performances of the proposed setup of bidirectional prosthesis on the basis of transcutaneous electrical nerve stimulation (TENS), three functional tasks were assigned involving both motor control and sensations, including activities of daily living. The task of location recognition requested that the subjects grasp an item with prosthesis and recognize whether it is positioned on the ulnar side, in the med palmar space or within the entire palm. The task of grip force control requested that the subjects grasp a dynamometer applying weak, medium and strong grasp intensity. Afterwards they investigated the performances of a bidirectional prosthetic setup with a more complex functional task. This task ("sensory blocks") requested that the subjects move as many as possible blocks in two minutes during central separation. Both tested subjects accomplished the task of location recognition with high accuracy (84-85% of correct answers). Such a high level of performance indicated that sensations evoked by stimulation of the ulnar or median nerve were easily recognizable for all subjects. When they were requested to generate four different intensities of grip force, they often complained that this task was difficult and that they were not certain how good they were at it. Although their performance was lower (the average correct answers rate was 75%) they were still able to perform this task efficiently (generating four statistically different force intensities). In a more complex task ("sensory blocks"), the blocks were not always placed on a bionic hand's palm, which forced the subjects to rely on their artificial sense of touch when deciding whether it was necessary to move their hand on the other side or not. The average result in the first session was 8 (8 meant the number of blocks moved within two minutes), while after four sessions, the result increased to 17 for the same period of time. Likewise, the mean number of mistakes was decreasing from one session to another as the subjects' confidence grew. In the last session there were no recorded mistakes. EEG data were obtained during TENS stimulation of one or both channels. Electrical stimulation generates clear somatosensory evoked potentials, which primarily occur on the contralateral hand. The head topography is according to the generator which is in the postcentral gyrus. Additional cortical regions, such as posterior parietal and frontal cortex, are activated 100 ms after the beginning of the stimulation (25). It was concluded that impulse width modulation with TENS represents a suitable choice for prosthetic sensory feedback, which enables users to determine the localization of the contact zone between prosthesis and an object, generate grip force at three different levels of intensity and accomplish more complex tasks of object manipulation (25).

Invasive methods of sensory substitution

D'Anna et al. in 2019 conducted a study about the possibility of using a closed loop upper-limb prosthesis and simultaneous intraneural tactile and position feedback (26). The previous studies have shown that the use of implanted electrodes, stimulation of surface nerves or sensory substitution provided tactile feedback in upper-limb amputees (27-29). These methods improved the function and prosthesis acceptance rate (30). However, existing information remains limited to a subset of affluent sensory signals available to healthy subjects. Proprioception, sense of position and moving of limbs, mostly have not been available in former prosthetic systems. In a previous study, it was shown how sensory substitution based on intraneural stimulation could provide positional feedback in real time and in conjunction with somatotopic tactile feedback (27). This approach enabled two persons with transradial amputation to regain almost natural, reorganized proprioceptive accuracy of high degree, whereby the accuracy of reproduction angle of the median wrist amounted to 9.1°, while the mean threshold of detection of passive motions was 9.5°, which was comparable with the results obtained with healthy subjects. Simultaneous providing information on the position and somatotopic sensory feedback enabled two subjects to successfully discern the size and hardness of grasped objects (75.5%). These results have shown that persons with transradial amputation can efficiently and simultaneously use tactile information obtained by means of somatotopic neural stimulation and position information obtained by sensory substitution (27). This study opens the pathway for more sophisticated, bidirectional bionic hands which will transfer complete, multimodal sensations.

Neural stimulation of the medial and ulnar nerve by use of transversal intraneural electrodes (TIMEs), demonstrated by Boretius T. et al. in 2010, provided the sense of touch to the upper-limb amputees which could be used for bidirectional prosthesis control (31). This bidirectional upper-limb prosthesis was tested in one patient with below-elbow amputation, whereby he was blindfolded and acoustically isolated to avoid the possibility of prosthesis control and determining its position according to the sound of its motor or by visual control of movements. In order to grasp an object and perform other motor commands, muscle signals were decoded. To enable subjects to "feel" an object, the electrodes provided nerves with electrical stimuli which were proportional to sensory information in real time. The researchers connected electrodes in the hand nerves with sensors placed in two fingers of the prosthetic hand and proportionally stimulated the nerves by hand motion. Provided feedback enabled the subject to efficiently adapt the grip force of the prosthetic hand, achieving three levels of force intensity. He was also able to use all restored sensations to achieve more complex perception, allowing identification of hardness and shape of three different objects by exploiting different characteristics of the evoked sensations. The research has shown that such an approach could improve the usage and efficacy of upper-limb prostheses (31).

Moreover, the previously conducted research has shown that by stimulating medial and ulnar nerve fascicule using transversal intrafascicular electrodes, according to the feedback provided by artificial sensors on the prosthetic hand, it was possible to make available physiologically adequate (almost natural) sensory information during decoding of various grip tasks in real time (32). The aim of the experiment was to test the subjects' capacity to modulate grip force by measuring output force by means of pressure sensors and to test the possibility to integrate sensations into functional tasks of identification of physical characteristics of objects from the everyday environment. This feedback enabled the subject to modulate the prosthetic grip force in an efficient manner without visual or auditory feedback. It was noticed that there were three different levels of grip force consistently used by the subject (32). The results also show that it is possible to achieve highly complex perception which will enable the subject to determine the hardness and shape of three different objects by use of different characteristics of the evoked sensations. Sense of touch was evoked in the area of innervations of the medial and ulnar nerve whereby it was used for bidirectional control of the sensitized prosthesis. For the duration of all experiments, the subjects had no access to visual or auditory information (32).

Tan D. et al (33) in 2014 showed in their research that it was possible to provide a stable, natural sense of touch for a longer period by implanting periphery neural interface in two subjects with upper-limb amputations. Electrical stimulation with the use of implanted peripheral neural electrodes which do not penetrate the nerve resulted in sense of touch at multiple points on the phantom limb with repeatable, stable answers in two subjects for the period of 16 and 24 months. The subjects described the obtained sensations as natural and without "tingling" or paresthesia. Different patterns generated different types of sensory perception at the same place on the phantom hand. Two subjects reported on tactile perception which they described as natural tapping, constant pressure, light touch and vibrating. Changing the average intensity of stimulation enabled control of the size of the region, while changing the frequency of stimulation allowed control of the strength of sense. Artificial sense of touch improved the ability of subjects to control the prosthetic grip force and to better manipulate fragile objects. Therefore, electrical stimulation by means of peripheral neural electrodes established a long-term sensory feedback after upper-limb loss (33).

ADVANTAGES AND DISADVANTAGES OF NEW METHODS FOR MORE INTUITIVE PROSTHETIC USE IN UPPER-LIMB AMPUTEES

Surface electromyography signal processing for the purpose of upper-limb prosthetic control represents a potentially interesting approach, but clinical applicability of this method is still limited (34). Several groups of researchers are now working on the solutions which could implant the electrodes into the nerve or muscle (iEMG OR iENG signals) or on "hybrid" solutions (TMR-Targeted Muscle Reinnervation, whereby surface EMG signals are recorded and processed but after surgical intervention). Targeted muscle reinnervation is the most advanced clinical solution at this point in time, and its advantage is that the neural function is physiologically connected to prosthesis control (35, 36). However, this method also has its shortcomings due to necessity of surgical intervention and method invasisvity which have not been completely solved by significant advantages regarding functionality and aesthetic appearance. Moreover, due to specific features of surgical interventions, this method would be more efficient in case of proximal amputation levels which more rarely occur. However, future research is required to gain a thorough insight about the advantages and disadvantages of this approach and its clinical applicability, with the necessity to develop more specific surgical procedures which would suit different neuroanatomic situations.

The results of the study on the use of implanted electrodes have shown that both iEMG and iENG signals can provide decoding of motor commands, while the main advantage of neural interface of the peripheral nervous system would be providing a feedback. Besides, recent studies have shown that there are significant limitations during the use of surface myoelectric signals, due to a lack of space for signal recording in high amputation levels and sensitivity of electrodes during setup (37).

When comparing iEMG and ENG signals as sources for control of bionic hand prostheses, several presumptions can be declared (which need to be experimentally confirmed in the future). The number of muscles (especially in the case of severe amputations or major muscle impairment) which could be used for recording EMG signals is lower, but still, it does not lessen the possibility of neural signal recording (at a certain degree).

1. In the case of iEMG, it is necessary to implant at least one electrode into each muscle. That would not be necessary with invasive electrodes of the peripheral nervous system which can record activities regarding control of different muscles from the same nerve. Besides, it is possible that decoding based on ENG signal processing is clearer than that based on EMG signals considering spatial 3-D changes in arm movement during control of arm prosthesis.
2. Moving the electrodes, with subsequent training of decoding algorhythms (10), should be easier when using neural electrodes which are fixed to the fibrous tissue.

The obvious disadvantage of the approach based on ENG signals is the invasivity of the method. However, this approach should be tested in new and more systematic experiments to better describe advantages and shortcomings of this method.

An important issue which should also be addressed is a lack of uniform metrics and experimental testing paradigm to enable comparison of different systems and algorhythms. That is the reason why Kim L. et al. published a special report on it in 2017, in which they presented a somatosensory psychometric questionnaire, which would help establish consistency and standardization of reporting in the future studies on somatosensory neural prostheses (38).

CONCLUSION

From a clinical point of view, the above-mentioned methods are very interesting and promising and show good results, but the studies are time-limited, without conducting long-term researches and proving the method applicability for a longer period of time, with larger sample size and in home conditions. All mentioned approaches are applicable and have good prospects in further clinical practice. Intraneural, extraneural, as well as surface approach, can be acceptable in a lesser or greater degree, depending on the etiology and level of amputation. From a clinical point of view, different approaches should be combined for obtaining more efficient control of bidirectional arm prosthesis and adequate sensory feedback.

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